HYDROCARBON DEVELOPMENT

SIMULATION OF EOR APPLICATIONS

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Abstract - India is an oil-importing, developing country. Oil-development strategies are largely based on the primary oil-production potential. We have developed a computer program to estimate the prospects for employing EOR in reservoirs with proven hydrocarbon deposits. The program simulates the production of oil and gas through primary, secondary and tertiary recovery stages and facilitates the use of primary and enhanced recovery together.

INTRODUCTION

Balance-of-payments (BOP) and other economic development problems of several oil-importing, developing countries (OIDCs) have been exacerbated by high oil prices in the past. OIDCs, which have commercially exploitable hydrocarbon resources, have stressed exploration and oil-field development, while enhanced-oil recovery (EOR) remains largely untapped.

India's oil-supply situation and prospects are reviewed, and a software program for simulating oil production through primary recovery and EOR is presented.

RATIONALE FOR INVESTING IN EOR TECHNIQUES IN INDIA

Oil-Import Bill and Balance-of-Payments

India is a net oil importer and is likely to remain so in the foreseeable future. Although India's oil-import bill has been reduced from 75% of foreign-exchange earnings through commodity exports in 1980/81 to 25% in 1987/88, India's total import bill has consistently exceeded export earnings in the 1980s. There have also been current and capital accounts deficits. Foreign-exchange inflows to neutralize the deficits have not been adequate since 1986/87, and India's foreign-exchange reserves have been reduced substantially.

According to the Government of India,[1] the BOP situation is under pressure owing to adverse medium-term factors such as (i) deceleration in the growth of indigenous oil production, (ii) protectionist tendencies in international trade, (iii) bunching

of loan repayment obligations, and (iv) unfavourable climate for concessional assistance. It may therefore be worthwhile to moderate imports of commodities like oil. Among such strategies is one to invest in EOR projects.

Indigenous Crude-Oil Supply Outlook

According to the Government of India,[2] the crude-oil production target for 1989/90 is 34.5 MMT. Even if only 34.5 MMT of crude oil were to be produced each year from 1989/90 through 2004/05, the total oil production in the 16-year period would be about 552 MMT, which is over 90% of the proven recoverable reserves of about 600 MMT. If this level of production is to be sustained by conventional methods of recovery alone, a massive exploratory effort will be required, particularly if the reserves-to-production (R/P) ratio of 10/1 is to be maintained until 2004/05. Exploration will also need to be accelerated because resource prognostications indicate that gas-oil ratios of future discoveries are likely be larger than present ratios. With India's oil demand likely to increase, oil-import needs will also increase.

The Role of EOR in India

EOR raises production rates from producing fields and increases recoverable reserves. Although there is some uncertainty associated with an EOR project, a fair idea of incremental recoveries can be obtained from a relatively low-cost pilot EOR project. India has made a beginning by investing in several EOR pilot projects in fields with declining production rates. Table 1

summarizes India's recent experiences in using various EOR techniques.

SIMULATION OF EOR APPLICATIONS

Past experience of India's Oil and Natural Gas Commission, suggests that data on reservoir rock and fluid properties collected while exploring a particular field are sufficient to identify suitable EOR techniques. This is the basic reason for developing a software package to devise a strategy for developing a newly-discovered field at the planning stage (TERI[3]). Our package is named SEnhORA (Simulation of Enhanced Oil Recovery Applications), is user-friendly, coded in TURBO Pascal, and can be used on an IBM PC compatible system.+ Figure 1 illustrates the basic capabilities of the package.

Oil-Recovery Mechanisms

SEnhORA simulates (i) primary recovery through a gas-cap drive, a water drive, or a solution gas drive (depending on the presence or absence of a gas-cap or a water aquifer), (ii) secondary recovery through pressure maintenance by gas injection or water flooding, and (iii) tertiary recovery through miscible flooding of either gases or chemicals. To simulate secondary and tertiary oil recoveries, a five-spot well configuration and a dispersed injection process are assumed. Other major assumptions are (i) all flows of reservoir and injected fluids are either linear or radial and (ii) the oil/gas payzone is homogenous.

+ For faster execution, it may be used with a co-processor and a TURBO-87 module of the TURBO Pascal compiler. A copy of the complete model formulation may be obtained from the authors on request.

SEnhORA does not simulate three-phase fluid movements. Therefore, recoveries by pressure maintenance are simulated for (i) water flooding only if gas saturation is below or just a little above the critical gas-saturation level and (ii) gas injection only when water saturation is at or just a little more than the connate saturation level.

For simulating recovery through miscible flooding, the model includes three cases, which are (i) miscible flooding following primary recovery, when neither gas nor water mobilities are high, (ii) miscible flooding following gas injection, when gas saturation is substantially above the critical gas saturation, and (iii) miscible flooding following water flooding, when water saturation is substantially higher than the connate water saturation.

Economics of Hydrocarbon Recovery

The net present values of costs are used to evaluate the relative economics of primary and enhanced recovery. Both capital and operating costs are included. The lead time required to install equipment and the economic life of all operating equipment are also accounted for. The sizes of all equipment for oil/gas treatment, separation, storage, etc. are determined on the basis of maximum recovery rates through the producing life of the oil field. For revenue calculations, oil and gas prices are specified exogenously and are then either held fixed at those levels through the producing life of the field or allowed to escalate according to exogenously specified annual

growth rates.

Working the Model

SEnhORA operates in three modes (i) complete optimization, (ii) simple optimization and (iii) single simulation. The recoveries may be maximized for (i) oil production, (ii) production of oil plus the oil equivalent of natural gas (hydrocarbon output), and (iii) profits (discounted revenues minus costs). The user can specify the variable that is to be maximized. The following key parameters are scanned: (i) the number of production wells n which, in a five-spot well configuration, equals the number of injection wells; (ii) m1*DelT, the time duration for primary recovery; (iii) (m2-m1)*DelT, the time duration for recovery through pressure maintenance; (iv) (m3-m2)*DelT, the time duration for recovery through miscible flooding; and (v) type of secondary and tertiary EOR techniques used.

In the complete optimization mode, the user specifies the time-step DelT; the model arrives at the values for n, m1, m2, and m3, as well as suitable EOR techniques (if no pressure maintenance techniques are used, m2 equals m1). Only EOR techniques that are technically suitable for use in the given field are considered. In the simple optimization mode, the types of EOR techniques to be implemented are specified exogenously and the values of n, m1, m2, and m3 are scanned. In the single simulation mode, all of the parameters are specified exogenously. In the latter two modes, the user may specify even those EOR techniques which do not meet the technical screening criteria. Values for hydrocarbon recoveries, fluid movements etc. are computed for

each time-step DelT. The computations for each time-step are iterative, and ensure that values of all geological and fluid-flow variables remain consistent.

SEnhORA generates a Report Table, which includes values for reservoir pressure, saturation levels for oil/gas/water/ miscible solution, fractional flows of gas/water/miscible solution, gas-oil/water-oil/miscible solution-oil ratios, and other parameters for each time-step DelT. The user may also specify the variables that should be printed in the Report Table.

Sample Run

Table 3 gives a sample output obtained from SEnhORA used in the simple optimization mode for a field for which technical data are given in Table 2. Relevant cost data are also entered in the SEnhORA input module. Table 3 shows that in the field under consideration, primary recovery should not continue beyond 18 years, when it would be best to commence dispersed gas injection (for pressure maintenance) and continue it for the next 14 years. After 32 years, it would be best to begin CO_2 injection. Although the oil-recovery rate would decline after the 32nd year, the results show that it will be worthwhile to continue production for another 58 years. Table 3 shows that as a percentage of oil and gas in place, (i) primary recoveries of oil and gas are 13.4% and 6.7%, respectively, (ii) secondary recoveries are 8.4% and 3.0%, respectively, and (iii) tertiary recoveries are 15.5% and 6.0%, respectively.

The results in Table 3 conform to the plans of the Oil and Natural Gas Commission about the types of EOR techniques to be used but not when they should be begun. This result is caused by simplifying assumptions that are built into the model. Further refinements in the model are necessary, particularly the incorporation of three-phase fluid flows, relaxing the assumptions of linear or radial fluid flows, and deriving analytically the exact composition of chemicals and gases to be injected for miscible flooding. Moreover, the model also needs to be expanded to include simulation of EOR through thermal methods.

Although our discussion pertains largely to India, the rationale for and implications of initiatives and efforts in EOR are of concern to several OIDCs. The software SEnhORA is only a beginning towards assisting the oil industry in framing long-term oil-field development strategies.

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2. Government of India, "Seventh Five Year Plan Document," Planning Commission, Parliament Street", New Delhi 110 001, (1985).

3. Tata Energy Research Institute, "Hydrocarbon Development : Simulation of EOR Applications," report of a project funded by the KDM Institute of Petroleum Exploration of the Oil and Natural Gas Commission, 7 Jorbagh, New Delhi 110 003 (June 1988).

Field	Type of EOR recovery	Date of commissioning	Additional recovery (% of OOIP)#
A	Micellar-Polymer	Aug. 1985	16%
B	Polymer	Apr. 1985	21%
C	Polymer	Apr. 1987	NA
D	Caustic	Dec. 1987	NA
E	Carbon-dioxide	Dec. 1989	NA
F	In-situ combustion	Apr. 1989	NA
G	In-situ combustion	Dec. 1989	NA
H	Steam Flood	May 1990	NA

+ Personal communications, KDM Institute of Petroleum Exploration, ONGC, Dehradun, India.

OOIP : original oil in place.

Area of field	394000000 m^2
Oil payzone thickness	15 m
Original gas cap volume	313542000 m^3
Oil payzone area contacted by water aquifer	0 m^2
Inital reservoir pressure	158.5 kg/cm^2
Bubble point pressure	158.5 kg/cm^2
Reservoir temperature	116.5 °C
Reservoir depth	1315 m
Angle of formation dip	31 degrees
Absolute permeability	538.8 md
Oil viscosity at initial conditions	0.445 cp
Water viscosity at initial conditions	0.320 cp
Gas viscosity at initial conditions	0.0175 cp
API gravity of reservoir oil	38 API°
Oil composition % of (c2-c7)	8 %
Oil composition % of (c5-c12)	12 %
Oil composition % of (c1-c7)	30 %
Presence of organic acids in oil : Yes [1], No [0]	1
Oil composition % of intermediates	12 %
Rock type : Sandstone [1], Carbonate [2]	1
Density of reservoir water	1000 kg/m^3
Density of reservoir gas (Standard Conditions)	780 kg/m^3
Porosity	0.22 fraction
Initial water saturation	0.562 fraction
Connate water saturation	0.562 fraction
Initial oil saturation	0.388 fraction
Initial gas saturation	0.044250 fraction
Critical gas saturation	0.050 fraction
Initial solution GOR (Standard Conditions)	110 m^3/m^3
Solution GOR at bubble point (Standard conditions)	118 m^3/m^3
Initial oil formation volume factor	1.34 m^3/m^3
Initial gas formation volume factor	0.0013 m^3/m^3
Gas formation volume factor at bubble point	0.0013 m^3/m^3
Initial Water formation volume factor	1 m^3/m^3
When reservoir pressure is less than bubble point pressure :	
- Oil compressibility	0.000124 cm^2/kg
- Gas compressibility	0.006250 cm^2/kg
- Water compressibility	0.000371 cm^2/kg

Reservoir pressure vs. solution GOR+	18	kg/cm^2	25	m^3/m^3
	50	kg/cm^2	48	m^3/m^3
	100	kg/cm^2	78	m^3/m^3
	150	kg/cm^2	104	m^3/m^3
	200	kg/cm^2	152	m^3/m^3
Oil saturation vs. effective permeability of oil.	0	fraction	0	md
	0.1	fraction	0	md
	0.2	fraction	5	md
	0.3	fraction	28	md
	0.4	fraction	538.8	md
	0.6	fraction	538.8	md
Gas saturation vs. gas to oil relative permeability ratio	0	fraction	0	ratio
	0.1	fraction	1.4	ratio
	0.15	fraction	7	ratio
	0.20	fraction	70	ratio
	0.29	fraction	105	ratio

+ GOR : gas-oil ratio.

Execution date	4/4/1989
Execution time	15:25:21
Data filename	AAA.SDS
Output filename	AAA.OUT
Reservoir type	Gas-cap drive
Oil in place	424990746.27 cu.m.
Gas in place	69989679874.00 cu.m.
Maximize	Profit
Simulation time-step	1 year(s)
Pressure maintenance recovery type	Gas injection
Miscible flooding recovery type	Carbon-dioxide
Number of production/injection wells	53
Primary recovery up to	18 years
Pressure maintenance recovery up to	32 years
Miscible flooding recovery up to	90 years

Time (Years)	Reservoir Pressure (kg/cm^2)	Cumulative GOR (cu.m/ cu.m)	Cumulative oil prod. (million cu.m.)	Cumulative gas prod. (million cu.m.)	Cumulative profits (Rs. billion)
Gas-cap drive					
0	158.5	-	0	0	-7.73
1	151.1	107.1	3.89	416.35	-1.59
2	144.1	103.0	7.62	798.39	3.72
3	137.5	102.9	11.06	1138.78	8.14
4	131.2	101.2	14.47	1464.64	12.11
10	99.0	92.1	33.80	3114.16	29.13
18	68.9	82.2	56.86	4676.14	34.14
Pressure maintenance (gas injection)					
20	68.9	80.4	61.96	4978.55	35.10
24	68.9	77.4	72.15	5583.36	36.60
28	68.9	75.2	82.35	6188.17	37.67
32	68.9	73.4	92.54	6792.98	38.21
Miscible flooding (carbon-dioxide)					
34	68.9	72.7	97.64	7095.39	38.49
40	69.1	71.0	111.45	7914.87	39.01
50	69.6	69.3	130.24	9029.28	39.35
60	70.0	68.3	144.78	9891.59	39.45
70	70.4	67.8	154.41	10463.73	39.48
80	70.9	67.5	160.11	10801.57	39.48
90	71.4	67.3	163.47	11001.07	39.48

Table 1. Status of EOR projects in India.+

Table 2. Sample data.

Table 3. Sample report for a simple optimization run.

Fig. 1. SEnhORA modules.